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Review

Remote sensing of ecosystem services: A systematic review

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abstract

Appropriate integration of remote sensing technologies into ecosystem services concepts and practices leads to potential practical benefits for the protection of biodiversity and the promotion of sustainable use of Earth's natural assets. The last decade has seen the rapid development of research efforts on the topic of ecosystem services, which has led to a significant increase in the number of scientific publications. This systematic review aims to identify, evaluate and synthesise the evidence provided in published peer reviewed studies framing their work in the context of spatially explicit remote sensing assessment and valuation of ecosystem services. Initially, a search through indexed scientific databases found 5920 papers making direct and/or indirect reference to the topic of "ecosystem services" between the years of 1960 and 2013. Among these papers, 211 make direct reference to the use of remote sensing. During the search we aimed at selecting papers that were peer-reviewed publications available through indexed bibliographic databases. For this reason, our literature search did not include books, grey literature, extended abstracts and presentations. We quantitatively present the growth of remote sensing applications in ecosystem services' research, reviewing the literature to produce a summary of the state of available and feasible remote sensing variables used in the assessment and valuation of ecosystem services. The results provide valuable information on how remotely sensed Earth observation data are used currently to produce spatially-explicit assessments and valuation of ecosystem services. Using examples from the literature we produce a concise summary of what has been done, what can be done and what can be improved upon in the future to integrate remote sensing into ecosystem services research. The reason for doing so is to motivate discussion about methodological challenges, solutions and to encourage an uptake of remote sensing technology and data where it has potential practical applications.

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1. Introduction

The last decade has seen the rapid development of research on the topic of ecosystem services and, increasing awareness of the economic value of ecosystem goods and services among decisionmakers and the general public (Morgan et al., 2008; Fisher et al., 2009; de Groot et al., 2010; Fish, 2011; de Groot et al., 2012; Maes et al., 2012; Bagstad et al., 2013). Following the release of the Millennium Ecosystem Assessment in 2005, a significant increase in the number of scientific publications on the subject has been observed (Egoh et al., 2007; Skourtos et al., 2010;White et al., 2010; Costanza and Kubiszewski, 2012). Preliminary work has made considerable advances in highlighting the links between social and environmental change influencing the capacity of ecosystems to maintain provisioning, regulating, supporting and cultural services (Costanza et al., 1997; Imhoff et al., 2004; de Groot, 2006; Reid et al., 2006; Deegan et al., 2012; Porras, 2012). Since then, spatially-explicit approaches have been used widely to map a multitude of ecosystems services, merging theory and practice to advance more effective sustainability and conservation actions (Sutton and Costanza, 2002; Costanza et al., 2008; Kienast et al., 2009; Liu et al., 2010; Murray et al., 2012; AlcarazSegura et al., 2013; Xie and Ng, 2013; Alamgir et al., 2014). Remote sensing plays an important role in the study of complex environmental interactions between natural and social systems, and has been used widely to quantify and map ecosystem properties and functions and infer ecosystem processes through a combination of existing instruments and data (Chopra et al., 2001; Ustin et al., 2004; Chambers et al., 2007; Muraoka and Koizumi, 2009; Palacios-Orueta et al., 2012). A key advantage of remote sensing is the capability to perform synoptic, spatially continuous and frequent observations resulting in large data volumes and multiple datasets at varying spatial and temporal resolutions (Estreguil and Lambin, 1996; Stolle et al., 2004; Knaeps et al., 2010; Baraldi and Boschetti, 2012; Atzberger and Rembold, 2013; Lewis et al., 2013). With the emergence of new and more sophisticated products, Earth observation data will continue to contribute extensively to research on modelling, mapping and valuation of ecosystem goods and services (Nemani et al., 2009; Verburg et al., 2009; Marghany and Hashim, 2010; Zinnert et al., 2011; Cabello et al., 2012). There have been numerous efforts to classify the services provided by ecosystems (Costanza et al., 1997; Daily, 1997; de Groot et al., 2002; MA, 2005), and more recent efforts on understanding the various contexts in which the ecosystem services concept has been used have the potential to move a step closer to the establishment of a meaningful and clear classification system. Nevertheless, there has not yet been agreement on a single classification scheme that provides a meaningful and consistent definition for ecosystem services, with different countries adopting different classification schemes, making assessment and valuation studies dependent on realities that are in many occasions site specific. (Faber, 2006; Boyd and Banzhaf, 2007;Wallace, 2007; Schmitt et al., 2013). Remote sensing measures reflected radiation, and by making use of such measurements and a forward model of the interaction of light with the Earth’s surface, it is possible to inversely estimate properties of the Earth’s surface such as land cover type, biomass, and leaf area index for each image pixel. Such properties represent spatially varying states at particular points in time. However, other properties of interest (e.g., land use; the function of the land) can only be inversely and indirectly inferred and mapped through contextual relations across space. Some ecosystem services, like primary production have a more direct relation with the reflected signal (e.g. satellite-derived chlorophyll measurements), while others, like climate regulation are only indirectly related to the reflected signal (e.g. satellitederived land surface temperature). Many economically important services, such as production of raw materials and food provision cannot be valued and assessed sufficiently by remote sensing alone and it may, therefore, be necessary to couple spectral information with other available datasets (Fig. 1). This paper provides a systematic review of the scientific literature related to the use of remotely sensed data within the explicit context of ecosystem services valuation assessment. We present examples from the literature that summarise (i) what has been done so far using remote sensing, (ii) what can be done in the future, and (iii) what can be further improved. For this purpose the selected literature was reviewed systematically, searching for specific information regarding the remote sensing platform used, remote sensing product used (e.g. land cover, biophysical indices, etc.) temporal coverage, and other relevant more technical aspects of remote sensing. 2. Methodology 2.1. Search and selection strategy This review focused on papers that used ecosystem services concepts, and made use of Earth observation data to estimate value flows of past and current availability of provisioning, regulating, habitat/supporting and cultural services. The approach taken to querying the literature consisted of a selective keyword search in specific scientific libraries (such as Scopus and Web of Knowledge). At each query, terms and keywords such as ‘Ecosystem Services’, ‘Ecological

Services', 'Environmental Service' 'Remote Sensing' and 'Earth Observation were used individually to produce an extensive list of articles. Using Scopus and Web of Knowledge the body of literature was searched based on a fixed set of inclusion criteria: (i) The literature should address ecosystem services as either main or secondary subject. (ii) The predefined keywords should exist as a whole in at least one of the fields: title, keywords or abstract. (iii) The paper should be published in a scientific peer-reviewed journal. (iv) The paper should be written in the English language. Fig. 2 represents the literature search and selection process. The initial steps of the search process in Fig. 2 returned 5920 published articles on the topic of ecosystem services alone. The search was subsequently refined by querying through the first set of results. Searching for predefined keywords and terms related to the 432 C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 Fig. 1. The transform of remotely sensed data into ecosystem services values and flows. topic of remote sensing, the total number of entries was reduced to 211 scientific publications. During the data extraction process, the selected publications were scanned to identify and extract information in the form of descriptive text and identify labels for automated sorting using a custom bibliographic matrix. During our literature search we aimed at finding studies meeting the criteria of a peerreviewed publication, and it should be available through indexed bibliographic databases. For this reason, our literature search did not include books, grey literature, extended abstracts and presentations. Throughout the exercise, ecosystem services found within the publications were categorised according to the classification scheme proposed by the Millennium Ecosystem Assessment (MA, 2005). The MA classification scheme has intrinsic challenges, when it comes to examining conditions and changes in ecosystems being referenced to more than one boundary definition. While there have been numerous attempts to create a definitive classification scheme for ecosystem services, there has not been yet an agreement upon which scheme offers a more meaningful and consistent definition (de Groot et al., 2002; Boyd and Banzhaf, 2007; Fisher et al., 2009). The option for the MA classification scheme comes from this being a widely recognised classification scheme that provided a comprehensive assessment of the state of the global environment (MA, 2005). 3. Results 3.1. Systematic review: what has been done. Total ecosystem services value depends not only on the natural phenomenon and location, but also on context and more subjective values related to societal wellbeing and cultural perceptions. In this context, current mapping methods based on remote sensing data are not sufficient alone for quantifying the full range of ecosystem services. At the same time, integration of ecosystem services valuation methods and remote sensing observation seems Fig. 2. Simplified literature search and selection flow process. C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 433 to be the only practical and realistic approaches to regionalise our understanding of complex interdependent socio-ecological systems. Where estimation is possible, translation from remote sensing data into estimates of certain ecosystem services values and flows may require data other than the spectral information itself. Therefore, if remotely sensed data are to be used to predict multiple ecosystem services it is required first to identify the nature of the relationship between the spectral information and the ecosystem service. Integration of remote sensing data in the explicit context of ecosystem services assessment has enabled numerous studies on how different social and ecological systems are interacting over time. For example, using land-use/land-cover classifications from time-series of Landsat images many studies were able to measure deforestation rates and, thus, estimate changes in provisioning of raw materials and genetic materials, for example, in China, Argentina and the United Sates (Wang et al., 2006;

Volante et al., 2012; Klepeis et al., 2013). Similarly, remote sensing data classified into land cover classes, combined with biophysical variables such as vegetation indices (VIs), are often used to quantify and map food production (e.g. Fegraus et al., 2012; Johnson et al., 2012; Castella et al., 2013). In this context, vegetation indices are used as a proxy for crop growth during the growing season, and then coupled with land cover and rainfall estimates to predict crop yield and enable forecasts of food production (e.g. Fuller, 1998; Konarska et al., 2002; Gong et al., 2010; Ivits et al., 2012; Palacios-Orueta et al., 2012). Muukkonen and Heiskanen (2005), in their study, used reflectance data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) together with a standwise forest inventory to estimate the biomass of boreal forest stands, using non-linear regression analysis and neural networks. Merging of VIs and land cover data may also be useful in creating models for prediction of the spatial distribution of species and biodiversity to estimate the availability of genetic materials (Dalezios et al., 2001; Moriondo et al., 2007; Saatchi et al., 2007; Nemani et al., 2009; Barman et al., 2010). Using land cover classifications produced by applying a support vector machine classification to time-series of Landsat imagery, Brandt et al. (2012) investigated how changes in forest type, loss of old-growth forest and ecotourism development were affecting the availability of provisioning services (raw and genetic material), habitat services (biological refugia) and regulating services (pollination and biological control). They found that changes in management practices and politics had a great influence in increasing and decreasing logging rates of high-diversity old-growth forest in the biodiversity hotspot of northwest Yunnan Province in southwest China. Krishnaswamy et al. (2009) investigated the relationship between the spectral distances and tree species diversity using a quantile–quantile plot method as an alternative to regressionbased approaches. Spectral distances were used in modelling forest type variability assuming that the larger the spectral distance the greater the species diversity within sites. A scale-dependent relationship was found between spectral and the floristic distances between areas. This approach can be applied to quantify and map multiple ecosystems services related to habitat, biodiversity, water and carbon storage. Combination of landscape metrics and time-series of land cover classifications from the Landsat Thematic Mapper (TM) and the Moderate Resolution Imaging Spectroradiometer (MODIS) matched with the proxy biomes from Costanza et al. (1997), has enabled numerous studies (e.g. Sutton and Costanza, 2002; Zhao et al., 2004; Chen et al., 2007; Zhang et al., 2007; Niu et al., 2012), with ecosystem service values (ESV) being associated to land cover classes assuming a linear relationship between land cover and market prices per unit area. Other studies, aiming at quantifying and mapping the spatiotemporal variation in ecosystem services values, based their methodology on time-series of land cover data from satellite sensor imagery coupled with landscape fragmentation and urban sprawl analysis (Kreuter et al., 2001; Su et al., 2012; Estoque and Murayama, 2013), econometric calculations (Niu et al., 2012), historical data (Cai et al., 2013) and meta-analysis of socio-economic variables (Camacho-Valdez et al., 2013). Integration of suspended particulate matter concentration and aerosol optical thickness data (from MODIS-Aqua and MODISTerra), land cover (from Landsat andMODIS-Terra), nutrient cycling (from SeaWifs) and NDVI (From Landsat and MODIS-Terra) has been used to measure spatial and seasonal patterns of water provision and flood regulation services (Muthuwatta et al., 2010; Ghobadi et al., 2012), erosion regulation, climate regulation and maintenance of habitat services (Chopra et al., 2001; Gong et al., 2010; Ke et al., 2011) in India, China, Uganda, Iran, Mexico and the United States. Furthermore, Nedkov and Burkhard (2012) have used water retention functions (of the vegetation and soil cover), digital elevation models and land use information to assess the capacities of different ecosystems to regulate floods. The resulting maps represent estimates of regional supply-demand balances converted into the ecosystems' flood regulating service capacity for the Malki Iskar river basin in northern Bulgaria. Multi-date imagery from the Sea-Viewing Wide Field-ofView Sensor (SeaWiFS), MODIS and Landsat sensors has been demonstrated to be effective in measuring and monitoring water purification, erosion regulation and natural hazard regulation services though estimates on the cumulative effects of shifts in size and spatial configuration of coastal habitats, vegetation cover, surface temperatures, coastal water salinity, chlorophyll, biomass and total suspended matter of marine ecosystems (Doron et al., 2011; Cloern and Jassby, 2012; Paerl and Paul, 2012). 3.1.1. Numbers and spatial distribution of research After the literature search, we found that the number of published research papers referring directly to the field of ecosystem services grew from 115 in 2005 to 5920 in 2013, denoting the rapid development of research within the field. The exponential growth of scientific publications in the field of ecosystem services research was followed similarly by an exponential increase in the number of published papers integrating Earth observation data in ecosystem services research (Fig. 3). The number of published research papers referring directly to ecosystem services and remote sensing has also increased significantly. The percentage increase in remote sensing and ecosystem services integrated studies relative to the total scientific production in the field of ecosystem services is presented in Fig. 4. To identify biophysical and socio-economic drivers of change in ecosystem service supply and demand, as well as long- and short-term trends, it is essential that the temporal coverage be of sufficient length and resolution. In particular, to monitor effectively the effects of time-sensitive socio-ecological interactions, it is necessary to use a remote sensing platform with a sufficiently frequent revisit period. Nevertheless, this is not an easy task since the availability of remote sensing data for long-term monitoring purposes is constrained by sensor characteristics (e.g. revisit time) and environmental factors (e.g. cloud cover). From Fig. 5 it is clear that the great majority of published material has focused on a small temporal extent. Several articles analysed more than 20 years temporal extent, but the number still falls short of what is required to perform 434 C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 0 5 10 15 20 25 30 35 40 45 50 Published papers Fig. 3. Number of papers published annually between 2001 and 2013. This plot represents only those research articles which integrate Earth observation data into the explicit context of ecosystem services research. 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 0 1 2 3 4 5 6 Yearly percentage Actual data Trend Line Fig. 4. Percentage of publications integrating remote sensing and ecosystem services relative to the total scientific production in the field of ecosystem services annually. The fitted regression line clearly indicates a positive trend. integrated analyses, aiming at continuous long-term monitoring of changes in ecosystem services supply and demand. The ecosystem services (and respective categories of services as defined by the Millennium Ecosystem Assessment (MA, 2005)) identified within the selected literature are presented in Fig. 6 in such a way that it is possible to visualise which services had a greater presence in research integrating Earth observation data into ecosystem services research. From the map in Fig. 7 it is evident that considerable gaps in geographical focus still exist around the world especially, rather surprisingly, in the African continent. Other areas lacking studies integrating remote sensing into ecosystem services assessment and valuation exist in Eastern Europe, Central America and the Middle East. 3.1.2. Remote sensing proxy data used in ecosystem services research Figs. 8–11 show how published works have used remotely sensed biophysical properties to map and quantify provisioning (Fig. 8), regulating (Fig. 9), habitat/supporting (Fig. 10) and cultural (Fig. 11) ecosystem services. The figures indicate that the biophysical properties used generally differ between each category of ecosystem service. For provisioning services (Fig. 8), the categories most well covered are water provision and food provision where seven remote sensing proxies were used; the least well represented categories are genetic resources and energy where only two proxies were used, respectively. The dominant ecosystem services proxy variables are respectively land cover (x¯ ~= 58%) and NDVI (x¯ ~= 35%). 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 0 2 4 6 8 10 12 14 16 18 20 22 24 26 Percentage of publications Temporal extent (years) Fig. 5. Temporal extent of studies identified within the literature selected. C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 435 Recreation Cultural Heritage Soil formation Primary production (Ocean/River) Primary production Nutrient cycling Habitat Biological Refugia Water regulation Water purification and waste treatment Pollination Natural hazard regulation Gas regulation Flood regulation Erosion Regulation Disturbance regulation Climate regulation Biological control Water Provision Raw Materials Genetic Resources Food Energy 0 2 4 6 8 10 12 14 16 Percentage of published papers Cultural Habitat/Support Regulation Provision Fig. 6. Percentage of publications using remote sensing to assess provisioning, regulating, habitat/supporting and cultural ecosystem services. For regulating services (Fig. 9), climate regulation, water purification and waste treatment are the most well covered categories where, respectively, eight and five remote sensing proxies were used. Important services such as biological control, disturbance regulation and gas regulation are the least well represented categories where only three remote sensing proxies were used. Again, land cover (x¯ ~= 47%) is appears as the dominant proxy variable used among all the categories, followed by NDVI (x¯ ~= 20%). For habitat/supporting services (Fig. 10), primary production (for marine and riverine environments) and biological refugia are the most well covered categories where seven remote sensing proxies were used. Soil formation, primary production (land) and nutrient cycling are the least well represented categories with only three remote sensing proxies used. Again, land cover (x¯ ~= 32%) is the dominant proxy variable used among all the categories of ecosystem services, although LAI (x¯ ~= 13%) and NDVI (x¯ ~= 7%) biophysical data have a significant presence. Estimates of cultural services are often used among stakeholders for planning, conservation, and environmental management. Nevertheless, there seems to be a lack of remote sensing proxy data in use (Fig. 11), with recreation services being covered by only three proxy variables, and recreation services being covered Fig. 7. Percentage of total published papers per study site integrating satellite remote sensing data within ecosystem services assessment. 436 C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 NDVI Land cover Sea Surface Temperatures Land Surface Temperatures LAI GPP Chl-a concentration NDVI Land cover Sea Surface Temperatures Land Surface Temperatures LAI GPP Chl-a concentration Energy Food Genetic Resources Raw materials Water provision 34% 66% 24% 45% 12% 6% 3% 7% 3% 15% 70% 15% 23% 56% 4% 4% 9% 4% 19% 55% 4% 4% 4% 4% 9% Fig. 8. Remote sensing variables used within the selected literature to assess ecosystem provisioning services. by only two remote sensing proxies. In the graph, land cover appears as dominant among all ecosystem services categories, followed by NDVI. In the case of cultural ecosystem services, it is in many ways challenging to produce satellite measurements of more subjective values related to societal wellbeing and cultural perceptions. 4. Potential of remote sensing: what can be done Climate regulating services (e.g. carbon storage and sequestration) can be estimated through quantification of net ecosystem exchange (NEE) of

CO2 flux, as NEE can be applied to determine the amount of atmospheric carbon stored in an ecosystem CDOM index LAI Land cover Water Layer Suspended solids Sea Surface Temp. NDVI Land Surface Temp. Elevation data Chl-a concentration CDOM index LAI Land cover Water Layer Suspended solids Sea Surface Temp. NDVI Land Surface Temp. Elevation data Chl-a concentration CDOM index LAI Land cover Water Layer Suspended solids Sea Surface Temp. NDVI Land Surface Temp. Elevation data Chl-a concentration CDOM index LAI Land cover Water Layer Suspended solids Sea Surface Temp. NDVI Land Surface Temp. Elevation data Chl-a concentration Biological Control Climate Regulation Disturbance Regulation Erosion Regulation Flood Regulation Gas Regulation Natural hazard regulation Pollination Water purif. & waste treatment Water Regulation 17% 33% 50% 2% 3% 36% 2% 2% 42% 11% 2% 60% 30% 10% 60% 10% 20% 10% 33% 17% 17% 33% 70% 20% 10% 40% 20% 20% 20% 33.33% 33.33% 33.33% 35% 16% 16% 16% 17% 52% 16% 16% 16% Fig. 9. Remote sensing variables used within the selected literature to assess ecosystem regulating services. C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 437 Thermal infrared Land Surface Temp. GPP Bathymetry NDVI LAI Land cover Water Layer Sea Surface Temp. Elevation data Chl-a concentration Thermal infrared Land Surface Temp. GPP Bathymetry NDVI LAI Land cover Water Layer Sea Surface Temp. Elevation data Chl-a concentration Biological Refugia Habitat Nutrient Cycling Primary production (Sea/River) Primary production (Land) Soil formation 8% 8.4% 8.6% 8.8% 16.6% 16.6% 33% 9.2% 9% 9.5% 54% 9% 9.3% 11% 33% 5% 12% 11% 28% 26% 12% 12% 26% 12% 12% 34% 34% 16% 16% 15% 57% 14% 14% Fig. 10. Remote sensing variables used within the selected literature to assess ecosystem habitat/supporting services. (Van Tuyl et al., 2005; Soojeong et al., 2006; Potter et al., 2008). Additionally, vegetation indices such as the NDVI, emissivity difference vegetation index (EDVI) and water band index, as well as the leaf area index (LAI), can also be used as indicators of net CO2 flux (La Puma et al., 2007; Dagg and Lafleur, 2010; Olivas et al., 2010; Hao et al., 2012; Kross et al., 2013). Air quality regulation as the capacity of atmosphere to cleanse itself, can be estimated by using trace gases and aerosols as indicators, since aerosol data, coupled with simulation models, enable the source of polluting air to be identified. Additionally, a change in the amount of dust build-up in the air will change the spectral reflectance of objects. Thus, pollutants can be detected from variation in the spectral reflectance (Chu et al., 2003; Emeis and Schaefer, 2006; Yong et al., 2010; Roots et al., 2011; Mozumder et al., 2013). Maintenance of soil fertility can be estimated from remotely sensed indices such as the non-photosynthetic vegetation (NPV), green vegetation (GV), NDVI and soil spectral mixture analysis, as an increase in NPV is suggested to be related to a decline in soil fertility (Numata et al., 2003). Moreover, reflectance data (within wavelengths 0.425–0.695 m) can be related to soil organic matter (SOM) and used as a proxy for soil fertility (Numata et al., 2003; Ji et al., 2012; Liu et al., 2013a). Other mineral features present in soils and detectable by remote sensing (e.g. salinity, iron-oxide content, and heavy metal contamination) change the reflectance properties of soils on bare lands and the surrounding vegetation indicating the past and current status of soils (Taylor et al., 2001; Kemper and Sommer, 2002; Wu et al., 2005; Melendez-Pastor et al., 2010). Erosion control regulation can be measured with medium resolution optical imagery (e.g. Landsat Thematic Mapper and Landsat NDVI Land Surface Temperatures Land cover Cultural Heritage Recreation 40% 60% 17% 33% 50% Fig. 11. Remote sensing variables used within the selected literature to assess ecosystem cultural services. Enhanced Thematic Mapper) by identifying the reflectance properties of the constituents of sediments (e.g. lithological composition, grain size and moisture content) potentially enabling the detection of eroded land and material deposition (Small et al., 2009). Vegetation indices and elevation data are suitable for predicting soil erosion risk, as mapping variability in vegetation cover and plant residue can help in revealing areas more or less prone to erosion. Remote sensing-based soil erosion models integrate NDVI, vegetation fraction cover, slope gradient and land use (from SRTM data) to estimate annual soil erosion rates (Hochschild et al., 2003; Rahman et al., 2009; Wu et al., 2011; Wang et al., 2013b). The diffuse attenuation coefficient (KPAR) for photosynthetically active radiation (PAR) can be utilised to assess water purification and waste treatment in ecosystems; since the availability of light is fundamental for phytoplankton and sea grass production, light attenuation can be used as a measure of turbidity or water clarity (Chen et al., 2009; Liu et al., 2013b). Thus, correlating satellite-derived reflectance data with in situ measured light attenuation enables assessment of water clarity and, hence, the water purification capacity of ecosystems (Behrenfeld and Boss, 2006; Zhu et al., 2009; Zhao et al., 2011). Earth observation data can be used to quantify the production capacity of forests and agro-ecosystems using biomass as an indicator. Narrowband and broadband vegetation indices such as NDVI, EVI, fPAR and LAI can be used as indicators of productivity in a crop growing season, as they are able to characterise variation in phenology and photosynthetic potential of crops and help identify the cropping cycle and growth (Kastens et al., 2005; Muukkonen and Heiskanen, 2005; Brown and de Beurs, 2008; Wall et al., 2008a; Wardlow and Egbert, 2008; Ling et al., 2009; Prabakaran et al., 2013). The capacity of ecosystems to deliver services such as the provision of energy through solar power can be identified using daily surface insolation data and atmospheric transmittance, extracted from optical and thermal infrared bands, in addition to models of aerosol optical depth and columnar ozone (Perez et al., 1994; Roujean, 1998; Morelli et al., 2012; Bhattacharya et al., 2013). In coastal regions, the capacity to provide wind energy can be estimated from radar imagery such as synthetic aperture radar (SAR), as it provides spatial patterns of wind speed, useful in mapping offshore wind resources (backscatter coefficients are physically related to wind speed by observing the roughness of the open sea) 438 C.C. de Araujo Barbosa et al. / Ecological Indicators 52 (2015) 430–443 (Johannessen et al., 1999; Hasager et al., 2002; Kozai and Ohsawa, 2007; Xiulin et al., 2013). Potential mass flow and rain-induced shallow landslide probability can be predicted using remotely sensed indices, such as vegetation indices, the soil brightness index, principal components transformation and terrain properties (Hyun-Joo et al., 2012; Shuwen et al., 2012; Yang et al., 2013) and applied in assessing natural hazard regulating services. Furthermore, radar interferometry (using SAR images) can be applied with image correlation techniques to generate displacement maps (e.g. the Line of Sight direction and the Azimuth direction), resulting in information that can be combined routinely to undertake landslide ground surface deformation monitoring by measuring the three dimensional surface displacement field at different epochs (Colesanti and Wasowski, 2006; Noferini et al., 2007; Righini et al., 2012; Raucoules et al., 2013; Tantianuparp et al., 2013). Remote sensing techniques applied to differentiate the composition of landscape/seascape can enable quantification supporting services such as nutrient and water cycling (Asner et al., 2004; Spillman et al., 2007). Water quality parameters such as dissolved oxygen, chlorophyll-a and turbidity are closely linked with changes in absorbance of natural radiation and can be detected by passive remote sensors(Xie et al., 2007; Wang et al., 2013a; Lin et al., 2014). Phosphorous concentration levels can also be used to track spatio-temporal water and nutrient cycling patterns across seascapes(Aighewi et al., 2013). Other remote sensing variables used to estimate nutrient cycling are related to measures of forest fragmentation and homogeneity, soil moisture and surface temperatures (Karl, 2002; Chang and Xuan, 2011). Monitoring and predicting wind storms is of particular importance in assessing the capacity of ecosystems to mitigate the negative effects of storms on coastal areas, croplands and associated infrastructure. Using satellite sensor data it is possible to accomplish this task; for example, using the MODIS reflective and emissive bands and artificial neural networks (Brakenridge et al., 2013; El-ossta et al., 2013; Notaro et al., 2013). Moreover, satellite sensor observations of damage caused by storms can also be used to assess an ecosystem's ability to regulate wind storms, since the damage extent on infrastructure and vegetation will most likely vary with the wind speed and strength. Valuable information about storm events (e.g. the trends in moderate-duration storms and mean sea level) can also be derived from TOPEX/Poseidon and Jason satellite altimetry data (Sadhuram et al., 2006; Han et al., 2012; Bhaskaran et al., 2013) Combinations of remote sensing data, stochastic and multiagent models have clear advantages in modelling and simulating land cover change, soil erosion, food production, and vegetation dynamics (Evans and Kelley, 2008; Aitkenhead and Aalders, 2011; Linard et al., 2013). Agent-based and stochastic modelling are potentially suitable approaches for expanding our knowledge about landscape functioning, climatological variability, biophysical constraints, economic and social dynamics. Therefore, these are potentially capable of providing insights into how highly complex systems behave and interact, and how they impact on the availability of ecosystem services (Jepsen et al., 2006; Wada et al., 2007; Brown et al., 2008; Evans and Kelley, 2008; Frank et al., 2012).

5. Discussion: suggestions for improvements

The use of remote sensing within ecosystem services research is still limited, and up until 2009 this topic had a relatively small presence in the literature. Nevertheless, the general trend indicates that the number of scientific publications integrating remote sensing into ecosystem services studies is increasing rapidly. This is no surprise given the possibilities for integrating spatial data into ecosystem studies and establishing relationships between remote sensing data and socio-ecological phenomena. The increasing exponential rate of integrated scientific studies is expanding our knowledge and pointing to areas for future development. In this section, we consider some of the weaknesses of the reviewed research studies and suggest improvements.

5.1. Correcting data

A few points of connection were found relevant within the selected publications. For example, in 85% of the publications there was no clear indication of whether the effects of the atmosphere on the reflectance values was taken into account prior to the analysis of the remotely sensed data for ecosystem services assessment and valuation (e.g. land cover classification process). 15% of scientific papers claimed to have performed atmospheric correction, although no reference was made to the algorithm applied. Many individual studies focused on mapping changes in the delivery of ecosystem services through time. However, to maximise the benefits of doing so, change detection should be done automatically in an operational environment, and the resulting information should be sufficiently reliable that it can be related effectively to what is observed on site (Beresford, 1990; Petit and Lambin, 2001; Song et al., 2001; Coppin et al., 2004; Sesnie et al., 2008; Zeng et al., 2012). This implies an operational atmospheric correction procedure to correct for the effects of aerosols, sun glint, thin clouds, cloud shadows and adjacency effects (Lambin, 1996; Cairns et al., 2002; Elmahboub et al., 2006; Vanonckelen et al., 2013). Where correcting for atmospheric effects is mandatory, even a simple atmospheric correction algorithm such as the dark object subtraction can increase the accuracy of land cover classification and change detection results (Moran et al., 1992; Song et al., 2001). A total of 28% of selected articles used single date imagery to assess ecosystem services; in these cases the application of an atmospheric correction algorithm may not be as essential as if image classification were to be performed formultiple dates (Kawata et al., 1990). 5.2. Land cover Remote sensing for the assessment and valuation of ecosystem services is still highly dependent on land cover data used as proxies for the actual ecosystem service. Land cover has been used as the main source of remotely sensed data in the majority of articles, serving as proxy data to spatial value transferbased modelling approaches, which have been demonstrated to be highly scale-dependent, producing inaccurate estimates when compared to primary data (Eigenbrod et al., 2010). By assuming a ESV = Area * Market price relationship, the valuation exercise will produce ecosystem services values that rely largely on the area measurements extracted from the satellite imagery. Therefore, ecosystem services valuation efforts in the context of remote sensing will be highly dependent on spatial resolution and image classification accuracy (Cai et al., 2013). Linking ecosystem functions and benefits to human well-being requires the knowledge of where the benefits of ecosystem services are manifest. Mapping the linkages between areas where ecosystem services are generated and where they are consumed is important for management and policy development (Cowling et al., 2008; Reyers et al., 2009; von Haaren and Albert, 2011; Bagstad et al., 2014; Sturck et al., 2014). In this context, through a combination of land cover/land use data, social and economic data the remote sensing based approach is critical in defining these links, especially when it comes to providing the information we need to define spatially and historically where the ES are produced and where these services are consumed by the beneficiaries.

Understanding the linkages between areas where ecosystem services are generated and where they are received is important for policy development, because, decisions by ‘upstream’ stakeholders to meet local requirements, may lead to positive or negative consequences from the perspective of ‘downstream’ stakeholders, at larger scales. Once receptor areas have been identified, then stakeholders who benefit (‘beneficiaries’) and those who either do not receive services (‘neutrals’) or who see a decrease in service supply (‘losers’) can be identified (node 3B). This approach facilitates a ‘needs analysis’ that can in turn inform strategic decision-making, though this is often complicated because stakeholders may be winners within the context of some ecosystem services and losers in relation to others, especially when evaluated over longer time horizons. The identification of beneficiaries allows spatially explicit representation of ecosystem service values. This in turn allows identification of strategies for equitable modifications to ecosystem service provision (node 3D). Appropriate measures to address the uncertainty of land cover classification are a prerequisite to any mapping exercise (Olofsson et al., 2013; Rocchini et al., 2013; Sexton et al., 2013). Through evaluation of the selected literature we identified the assessment of thematic accuracy of land cover classification to be another important issue, only 17% of the studies within the selected literature appeared to have performed accuracy assessment on the land cover classification results. A variety of measures were used to describe the accuracy of land cover classification. For example, to summarise the results of an accuracy assessment, authors used the overall proportion of area and/or pixels correctly classified, the Kappa coefficient of agreement, and the user’s and producer’s accuracies. The applicability of land cover data relies on its quality, and in this context it is critical to assure the validity of the classification results and their suitability for any particular purpose. In addition, the error budget included in the classification will most likely propagate through the analyses linking the final land cover map to other datasets used for the ecosystem services valuation at any given spatial scale (Congalton and Green, 1993; Gahegan and Ehlers, 2000; De Clercq et al., 2009). 5.3. Vegetation Vegetation indices derived from satellite sensor images have become a major data source for monitoring ecosystem services, such as climate regulation, primary production and natural hazards regulation that are linked to vegetation condition. Nevertheless, none of the studies reviewed accounted for the influence of sensor characteristics in the calculation of their NDVI values. For example, NDVI values derived from MODIS products were applied in capturing vegetation phenology, although the relatively coarse 500 m spatial resolution and smoothing forced by the 16 day BRDF model inversion reduces their ability to capture fine scale temporal variation in phenology (Jing et al., 2004; Hadjimitsis et al., 2010). Difficulties may, thus, emerge in detecting inter-annual variation in phenology, and estimating phenological parameters such as the onset of greenness (OG), length of season and end of senescence, affecting directly the robustness of relationships involved in estimating and forecasting crop cycles and crop yield (Fuller, 1998; Basnyat et al., 2004; Brown and de Beurs, 2008; Drolet et al., 2008; Wall et al., 2008b; Mkhabela et al., 2011). 5.4. Spatial scale The spatial scale at which ecosystem services are assessed through remote sensing will greatly influence the resulting ecosystem services monetary values, as changes in area within the land cover types will impact the amount of change in total ecosystem service values (Konarska et al., 2002; Nelson et al., 2009). It is important to understand how ecosystem assessments and monetary valuations will vary with changes in spatial scale, especially with most ecosystem services assessment and valuation studies being supported by multi-sensor land cover data. For example, if using data from multiple sensors (assuming that they have different spatial resolutions), the resulting land cover classes will differ in area (Boumans et al., 2002), and consequently affect ecosystem service valuations. Depending on the spatial resolution, data from different sensors will most likely produce different estimates for the same area (Konarska et al., 2002). Another issue will emerge if the image scene contains subdominant and rare classes. These exist largely at the sub-pixel scale and, thus, are difficult to resolve with thematic coarse resolution satellite sensor imagery (Serra et al., 2003; Aguirre-Gutierrez et al., 2012). Furthermore, due to the coarse spatial resolution (both spatial and spectral) of some satellite sensors, land cover classes that tend to appear in small patches are often omitted from the final classification product, and consequently replaced by other dominant classes surrounding them (e.g., using the maximum likelihood classification method). Depending on the classification method used, the chosen classifier might be dominated by the prevalent class and fail to account for the rare examples. As a result, small and rare classes may be underestimated and the large classes overestimated (Congalton, 1991; Hammond and Verbyla, 1996; Doan and Foody, 2007). 5.5. Temporal extent Observation of patterns in human activities over time, and the capacities of different ecosystems to provide services under different scenarios of land use change is a key element in most social and ecological studies. In the literature selected 44% of studies have used Earth observation data corresponding to a temporal extent greater than ten years, and within this value 20% of studies concentrate on extending observations to more than twenty years. Ecosystem services studies would benefit greatly from extensive repeat surveys, as they are extremely useful in detecting and analysing the temporal and spatial dynamics of ecosystem services and their likely beneficiaries. For example, if an area is converted from forests to agricultural land this inevitably causes a loss of critical habitat, and any ecosystem services study that considers only a short period of time will fail to accurately assess the costs and benefits of that land use/cover conversion and the differences in the timing of subsequent impacts. Consequently, research efforts integrating Earth observation data into ecosystem services studies will need to ensure that the temporal extent of the analysis is consistent with the temporal extent of the projected impacts, such as in studies focused on long term monitoring of shifts on socioeconomic conditions and climate change. 5.6. Cultural ecosystem services Earth observation data can be used to help define high priority areas for tourism and conservation, and link concepts of heritage and identity to the landscape (Turner et al., 2003; Naidoo and Ricketts, 2006; Cabello et al., 2012). However, assessment and valuation of cultural ecosystem services through remote sensing have been focused mainly on extracting data to feed into Geographic Information Systems (GIS) (Bender et al., 2005; Gret-Regamey et al., 2008; Sherrouse et al., 2011). The GIS object based approach is usually not sufficient to reveal the complex behaviour emerging from the interactions between social and ecological systems, which in turn is critical to define and constrain any given cultural ecosystem service (Brown, 2005). In this context, cultural services and community values tend to be overlooked and not entirely considered (Raymond et al., 2009; Daniel et al., 2012).

The application of remote sensing combined with economic and social data (both quantitative and qualitative) may help to stablish the necessary abstractions we need when accounting for cultural ecosystem services. For example, the combination of satellite data (e.g. crop productivity, land cover, precipitation, and land surface temperatures) individual and group choices, in a multi-agent modelling environment, has the potential to provide estimates of cultural ecosystem services. Inevitably, the modelling exercise will produce valuable data that can be used as input into dynamic simulation models, improving our understanding about the nature of changes occurred at varying spatial scales through time. Assessment and valuation of cultural ecosystem services strongly depends on perceptions and expectations of users and stakeholders. Medium resolution satellite imagery (e.g. 30 m resolution Landsat images) can be used to inform users and stakeholders, creating more intuitive representations of the environment, influencing expectations and choices, and inevitably contributing to participatory and deliberative decision making. In future studies, interdisciplinarity integrating more of RS into estimating cultural ecosystem services may provide the necessary means to move beyond measuring the value of physical stocks above the Earth’s surface, and start systematically valuing the cultural services provided to society. 6. Conclusions This systematic review summarises research progress towards the use and integration of remote sensing data within the context of ecosystem services valuation and assessment. Individual examples from the literature were reviewed to suggest what has been achieved so far, what can be done and what can still be improved when using remote sensing data to estimate ecosystem services. Through a systematic review of the literature on remote sensing for ecosystem services assessment and valuation studies, it was possible to describe quantitatively both the overall numbers of publications through time, and the relation between the range of remotely sensed biophysical properties predicted and the ecosystem services which they are used to estimate. The results show which ecosystem services are the most measured from space, what kind of remote sensing data have been applied more frequently in estimating these ecosystem services, the temporal resolution of these research efforts, and where in the world more research is still needed. Several basic technical issues need to be addressed more frequently, as these issues will influence the overall uncertainty budget, as follows: the accuracies of classification results and biophysical data used as proxies, the different spatial, temporal and spectral resolutions of the satellite sensor system (in many cases this restricts the utilisation of the remotely sensed data) and, when possible, the need to account for the dominant conditions at the time of image acquisition (e.g., atmospheric interference, viewing geometry, etc.). Future research needs to account for the fact that effective mapping of the full range of ecosystem services is currently beyond the capabilities of remote sensing alone and, therefore, more concerted research is needed to overcome this and other limitations, for example, through fusion of remotely sensed data with information from other sources.

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